

A Lightweight Embedded System for a Hybrid Autonomous Mobile Robot

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ABSTRACT

Autonomous mobile robots are increasingly used in cost-constrained settings. This work presents the design and implementation of a hybrid robotic platform that combines autonomous navigation with manual control through Bluetooth communication. The platform uses two ultrasonic sensors combined with directional sampling for environment perception. Distance measurements are evaluated across multiple orientations to select motion based on maximum available space, while obstacle handling is performed through a sequential response including stop, retreat, and reorientation. Experimental evaluation showed consistent obstacle detection and stable movement, based on sensor measurements and low computational requirements.

CCS CONCEPTS

• **Computer systems organization—Embedded systems**; • **Computer systems organization—Robotic control**; • **Hardware—Sensor applications and deployments**;

KEYWORDS

Autonomous mobile robots, Lightweight Embedded systems, Sensor-based navigation, Obstacle avoidance, Wall following control

1 INTRODUCTION

Recent advancements in mobile robotics have focused on developing cost-effective and resource-efficient platforms for constrained environments [1]. Despite this progress, achieving reliable navigation remains challenging under limited hardware and varying conditions [2].

Basic tasks such as obstacle avoidance and wall following can be implemented on resource-constrained embedded implementations. Yet, their performance in real-world conditions often depends on factors such as sensor placement and the surrounding environment. Many existing implementations operate either in a fully autonomous mode or under direct user control [3]. This separation limits a robot's versatility, particularly in dynamic environments where a human operator may need to provide guidance or correct navigation errors in real-time.

To address this issue, this work implements a hybrid control approach that combines autonomous operation with user intervention. Instead of relying on computationally demanding methods, the framework applies threshold evaluation combined with directional comparison. This keeps computational requirements low while maintaining reliable performance indoors.

In addition, Bluetooth communication is integrated into the framework, allowing the user to switch between control modes during operation without interrupting functionality. This provides

a balance between performance and cost, making it suitable for rapid prototyping and educational applications.

2 RELATED WORK

Research in mobile robot navigation often follows two main directions: more complex adaptive control methods and simpler, task-focused designs. Fuzzy logic controllers are commonly used for wall-following because they provide smoother and more adaptable behavior compared to basic "if-then" rules [4]. However, they usually require more computation and careful parameter tuning, which can be difficult to support on low-power embedded hardware.

On the other hand, several studies have shown that standard microcontrollers combined with Bluetooth communication can handle basic obstacle avoidance and remote control [5]. These implementations demonstrate that reliable operation is possible even with limited processing power, despite being designed for specific tasks and offer limited flexibility.

At the same time, many recent approaches rely on high-precision sensors to improve navigation accuracy. While this can improve performance, it also increases system complexity and processing demands, which is not always ideal for lightweight platforms. In this work, a different approach is taken by combining autonomous and manual operation within a single framework. By keeping the control logic minimal, the setup remains effective while still providing enough flexibility for typical indoor environments.

3 PROPOSED SYSTEM

The proposed architecture combines sensing, processing, communication, and actuation within a single embedded design that supports both autonomous and user-controlled operation, as illustrated in Figure 1. Distance data is evaluated across multiple orientations to select the direction with the greatest available clearance, while Bluetooth commands allow user-driven mode changes and motion overrides.

A co-design approach integrates sensing, control, and movement [6]. The overall structure is divided into functional components: ultrasonic sensors collect distance data, the controller processes calibrated readings, and the actuators execute the selected motion.

To maintain a lightweight design, all operations are handled by an Arduino-based platform, avoiding additional processing units. The control strategy combines low computational cost with multi-step reactive behavior, including obstacle recovery, directional comparison, and reassessment. Nevertheless, performance may decline in dense obstacle layouts, highlighting the trade-off between compact implementation and navigation capability.

To enhance spatial perception without increasing sensor count, the front ultrasonic module is mounted on a servo mechanism that reorients the sensing direction for multi-direction evaluation.

Measurements collected from different orientations are compared to estimate the most favorable movement direction. This approach improves environmental awareness while preserving a compact hardware configuration.

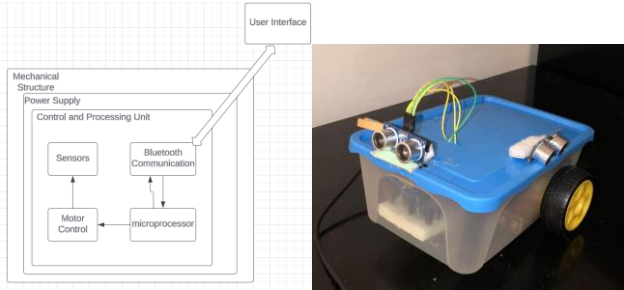


Figure 1: System architecture, and robot prototype.

3.1 Hardware Architecture

The hardware architecture was built around a microcontroller that coordinates sensing, communication, and motor control functions as shown in Figure 2. Two ultrasonic sensors were used, one at the front for obstacle detection and one on the side for wall-following tasks in indoor environments. The prototype is assembled within a compact tupper-based chassis, providing a minimal, cost-efficient structure for component integration.

The front module is mounted on a servo motor to extend coverage. Positioning affects reliability, particularly for the side unit, where small misalignments caused unstable readings.

Movement was achieved using a differential drive configuration with two DC motors controlled through an L293D driver module. For wireless communication, an HC-05 Bluetooth module is used, allowing command input and mode switching [7]. The design is reproducible with reduced power consumption.

A split power configuration was adopted to isolate control and actuation loads. The microcontroller is powered separately from the motor subsystem, reducing voltage fluctuations during motion. This design choice improved signal stability, particularly during rapid direction changes where simultaneous motor activation introduced transient voltage drops.

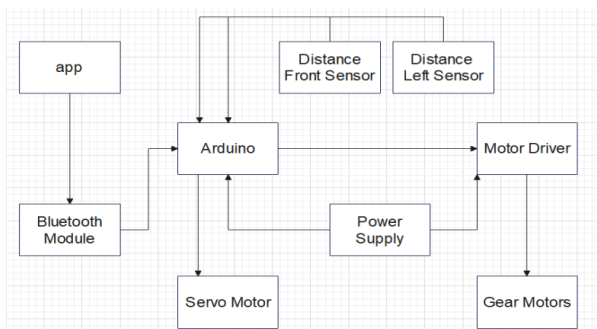


Figure 2: Hardware architecture.

3.2 Software Architecture

The control loop supports both user input and autonomous navigation. In manual mode, Bluetooth commands are translated into motion actions such as forward, backward, left, right, stop, ON/OFF, obstacle avoidance, and wall following. Response is typically immediate, with minor delays caused by asynchronous communication.

Wireless communication is implemented using a serial interface operating at 9600 bps. Although sufficient for command transmission, this data rate introduces small delays during rapid updates. These effects appeared during frequent mode transitions, reflecting the trade-off between communication simplicity and responsiveness.

During autonomous operation, motion decisions rely on averaged ultrasonic measurements combined with threshold evaluation. Each distance value is calculated by multiple samples and corrected using a regression-based calibration model, improving stability and reducing measurement noise.

As illustrated in Figure 3, the navigation logic integrates threshold-based safety checks with directional selection derived from maximum sensor readings [8]. When an obstacle is detected below the safety threshold, motion is halted and a structured recovery sequence comprising stopping, retreating, turning, and reassessment is initiated. At safer distances, the platform continues forward or performs corrective turns based on available clearance. Wall tracking begins with nearest-wall detection, followed by alignment and continuous correction to maintain path stability. This behavior is governed by a sequential decision-making process that combines threshold evaluation, directional comparison, and corrective actions, while prioritizing obstacle avoidance in cases of conflict [9]. The implementation follows a command-driven structure where Bluetooth inputs and sensor readings determine movement behavior.

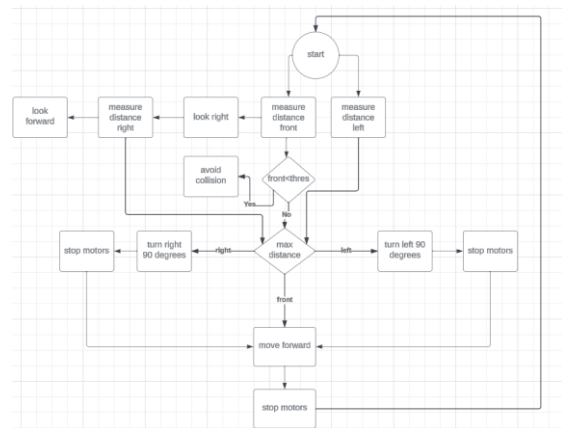


Figure 3: Flowchart of the obstacle avoidance algorithm.

4 RESULTS

4.1 Experimental Setup and Obstacle Avoidance

The platform was evaluated in an indoor setting with walls, obstacles, and open areas. A total of 20 experimental observations

were recorded, as shown in Figure 4. Prior to testing, the ultrasonic sensor was calibrated using regression-based correction. This adjustment improved measurement consistency near the decision threshold, leading to more stable transitions between motion states. Figure 4 illustrates the relationship between measured distance and the corresponding motion decision. The dashed horizontal line represents the safety threshold at 20 cm, separating forward movement from avoidance behavior. Distances above this value allow forward motion, while lower values trigger stopping and directional adjustment.

In general, short distances led to avoidance actions, while larger values allowed continuous movement. In 16 out of 20 observations, the selected action matched the expected response, corresponding to an accuracy of approximately 80%. Avoidance actions are mainly concentrated near or below the threshold, indicating correct detection of potential collisions.

Some deviations are observed, where directional changes occurred at higher distances. These cases are attributed to secondary factors, such as lateral corrections during wall tracking or user-triggered commands. Despite these variations, behavior remained consistent across trials.

Overall, the results indicate stable motion based on directional selection and reactive obstacle avoidance under typical indoor conditions, with clear separation between movement states driven by sensor input.

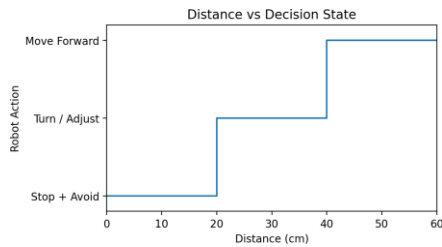


Figure 4: Distance vs Robot State

4.2 Navigation Strategy and System Response

Navigation is based on continuously selecting directions with the most available space at each decision step. Figure 5 shows how distance measurements relate to movement decisions across multiple trials and different spatial conditions.

Short distances triggered avoidance, while larger values allowed forward motion. In some cases, direction changes occurred at higher distances due to wall-following adjustments or manual input, reflecting the flexibility of the hybrid method during operation.

Movement transitions were generally smooth, although small delays were observed during direction changes, especially in tighter areas or near obstacle boundaries.

5 CONCLUSION AND OUTLOOK

This study presented a hybrid platform that combines autonomous navigation with user control. By using ultrasonic sensors together

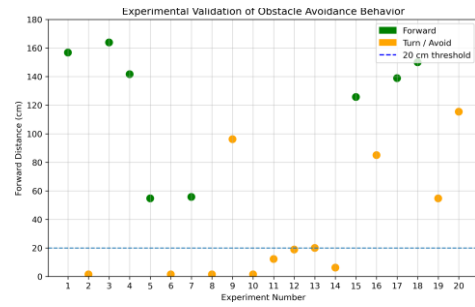


Figure 5: Forward distance across experiments. Green: forward motion; orange: turn/avoid. Dashed line: 20 cm threshold.

with a structured control method, the platform performs obstacle avoidance and wall following without requiring demanding processing resources or additional hardware components.

Results show consistent indoor navigation, with limited sensing and compact logic. In most test scenarios, performance remained stable, with movement adapting to available space and nearby obstacles. In more constrained layouts, where behavior became less consistent, additional sensing or improved decision strategies could further improve responsiveness and accuracy.

Overall, the proposed approach enables consistent motion control using a compact hardware setup and a clear control structure. Beyond technical performance, the design supports low-cost solutions for assistive and indoor applications. At the same time, the results highlight limitations under more demanding conditions, particularly in areas with dense obstacles or restricted space, where sensor readings may become less stable.

Future work aims to strengthen system robustness by incorporating additional sensing and more refined control logic. This would support improved handling of dynamic environments while boosting adaptability and overall system performance across varying operating conditions.

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